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Fugitive Emissions and Health Implications of Plancha-Type Stoves

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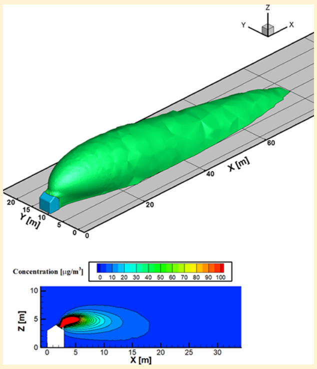
Supporting Information

ABSTRACT: Plancha-type stoves have been widely disseminated in Mexico and Central America, but the contribution of fugitive emissions from these stoves to indoor air concentrations has been poorly quantified. In this study, fugitive emissions were measured for four plancha-type cookstoves most disseminated in Mexico (Patsari, ONIL, Ecostufa, and Mera-Mera). In controlled testing, fugitive emissions from plancha-type chimney stoves (n = 15 for each stove) were on average 5 ± 3% for $PM_{2.5}$ and 1 ± 1% for CO, much lower than defaults in WHO Guidelines (25 ± 10%). Using a Monte Carlo single zone model with locally measured parameters, average kitchen concentrations resulting from fugitive emissions were 15 ± 9 $\mu g/m^3$ for $PM_{2.5}$ and 0.06 ± 0.04 mg/m^3 for CO. On the basis of these models, plancha-type stoves meet benchmarks for WHO Air Quality Guidelines (AQG) Interim Target I for $PM_{2.5}$ and the 24 h AQG for CO, respectively, with on average 97% of homes meeting the guideline for $PM_{2.5}$. Similarly, all four plancha-type stoves were ISO IWA Tier 4 for indoor emissions of CO and Tier 3 for indoor emissions of $PM_{2.5}$. Three-dimensional computational fluid dynamics (CFD) analysis was used to estimate neighborhood pollution impacts of upstream chimney emissions. When chimney emissions were included as background concentrations combined with indoor contributions from fugitive emissions, plancha-type stoves would still meet the WHO AQG Annual Interim Target I for $PM_{2.5}$ and the 24 h AQG for CO for the scenario modeled in this study.



1. INTRODUCTION

Field studies have shown that well-functioning plancha-type chimney stoves that vent emissions outside the home result in significant exposure benefit compared to open fire stoves,[1] as only a fraction of the emissions enter the kitchen via fugitive emissions and reinfiltration, especially if the plancha stove is used exclusively and other combustion sources are removed from the kitchen.[2] Plancha-type cookstoves have been widely disseminated in Mexico, Guatemala, El Salvador, Honduras, and Nicaragua, where they have become widely accepted in local communities, and somewhat less in Panama and Costa Rica.[3] In Mexico, a total of more than 600 000 plancha-type stoves were disseminated between 2007 and 2012, mostly through the *Programa Nacional de Estufas de Leña*.[4] While plancha-type cookstoves are very popular and widely disseminated in Latin America, they do not easily fit into performance frameworks currently being developed by the cookstove community.

The International Workshop Agreement (IWA) 11:2012 established tiers of performance for cookstove efficiency, emissions, and safety.[5] The IWA emission benchmarks were established with tiers for indoor emission rates and for total emission factors (based on useful energy delivered) spanning performance of traditional open fires (Tier 0) to aspirational targets (Tier 4). Although the fraction of emissions that does not go up the chimney (fugitive emissions) may be used to estimate the tiers for indoor emissions, the protocols/testing methods for simultaneous assessment of fugitive and chimney emissions have not yet been established. Further, the indoor emission tiers do not account for the reinfiltration of emissions from the chimney back into the indoor environment.

The World Health Organization (WHO) Indoor Air Quality Guidelines recommend emission rates for both vented and unvented stoves,[6] where the emission rate for vented stoves used a normal distribution for the fraction of emissions entering the kitchen (fugitive and reinfiltration), ranging from 1% to 50% with a mean of 25% and standard deviation of 10%

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of the emissions from an unvented stove. The estimate, however, was roughly based on the ratio of concentrations in homes with chimney stoves to those without chimney stoves rather than direct studies of fugitive emissions. The contributions from reinfiltration were also not included in the WHO guidance. Cognizant of the gaps in information for specific stove types, the IWA workshop attendees recommended that new protocols be developed or current protocols be updated to more adequately address a larger number of stove and fuel types, including plancha-type stoves.

Indoor pollutant concentrations in a kitchen with a plancha stove are a function of fugitive emissions from the stove, reinfiltration of emissions from the chimney of the same stove back into the home, and infiltration of ambient pollutants from other external sources and upstream village stoves, in addition to ventilation rate, room volume, and mixing. Determination of whether plancha-type stoves should be promoted in an area to actually achieve substantive health benefits therefore depends on the amount of fugitive emissions from the stoves, the density of homes that contribute to downwind neighborhood pollution levels, and relative costs and accessibility of cleaner fuels, in addition to considerations relating to adoption, user preferences, and cooking tasks. For plancha-type stoves to be better incorporated into ISO:IWA 11:2012 tiers of performance for emissions and for better estimation of relative health benefits that may accrue from promotion of plancha-type stoves, fugitive emissions and the impact of the chimney emissions on other village houses downstream need to be evaluated.

In this paper, fugitive emissions for four Mexican plancha-type stoves are presented that show plancha stoves meet ISO IWA benchmarks for indoor emissions of $PM_{2.5}$ Tier 3 and CO Tier 4 with mean kitchen concentrations below the WHO Interim Target 1 (WHO IT1) when combined with local parameters on building ventilation rates, room volumes, and cooking times. Further, the impact of the chimney emissions on surrounding houses downstream is demonstrated through the application of a three-dimensional computational fluid dynamics (CFD) analysis to establish criteria for housing densities where plancha-type stoves could be promoted without major neighborhood pollution effects in surrounding houses.

2. MATERIALS AND METHODS

One of the key parameters that need to be measured for adequately estimating the impact of chimney stoves on indoor air pollution is the fraction of pollutants that do not exit through the chimney but leak through the combustion chamber entry or from other parts of the stove into the kitchen, known as fugitive emissions “f”. For example, as stated above, the WHO roughly assumed that, for chimney stoves, f ranges from 1% to 50% with a mean of 25% and standard deviation of 10%.[6]

2.1. Measurements of Fugitive Emissions. Fugitive emissions were measured as a fraction of the overall emission by using two nested hoods to capture separately the emissions through the chimney and fugitive emissions to the room at the same time (Figure S1), consistent with the system specified in ISO Standard 19867-1. Flue emissions and fugitive emissions were measured for four plancha stove models with a chimney (Patsari, ONIL, Mera-Mera, and Ecostufa; see Medina et al.[7]), which are the models most disseminated in Mexico, using the Water Boiling Test (WBT) protocol version 4.2.3.[8] Fuels used were White Oak (*Quercus spp.*) in all tests with average moisture content on a wet basis of 7.0 ± 0.6% with a range of 6.1−8.2% measured using a Protimeter Timbermaster Wood Moisture Meter (GE, Billerica, MA). Further details are described in Ruiz and Masera.[9]

Measurement of CO_2 and CO emissions was performed using a Laboratory Emissions Measurement System (LEMS) (Aprovecho Research Center, Oregon USA), and a Q-Trak (Model 7575, TSI Inc., Shoreview, MN) was used for fugitive emissions. Real-time concentrations are measured in both equipment using a nondispersive infrared (NDIR) sensor for CO_2 and an electrochemical cell to measure CO. CO_2 and CO sensors were calibrated using zero air and a mixture of 500 ppm of CO and 5000 ppm of CO_2.[10] Factory calibrated Q-trak have been shown to perform well in quantifying lower concentrations of CO_2 and CO in comparison with stainless steel canisters collected during the same emissions tests and analyzed by GC FID equipped with preconcentrator and methanizer.[11] $PM_{2.5}$ mass from both flue emissions and fugitive emissions was collected isokinetically with a $PM_{2.5}$ cyclone on fiberglass filters for gravimetric determination.[12] The sample flow for fugitive emissions was 4 L/min with a 47 mm filter and 16.7 L/min with a 102 mm filter for chimney emissions, and all filters were weighed on a microbalance with a resolution of 1 μg.

2.2. Impact of Fugitive Emissions on Indoor Air Quality and Neighborhood Air Pollution. A Monte Carlo single zone model was used to estimate the impact of fugitive emissions from plancha-type stoves on indoor air quality[6] and is described mathematically in the Supporting Information. The impact of the chimney emissions on surrounding houses downstream is demonstrated through the application of a three-dimensional computational fluid dynamics (CFD) analysis described in further detail with methodology validation in the Supporting Information.

Indoor air concentrations estimated using the single-zone model and impacts of emissions on neighborhood pollution were based on locally measured housing characteristics and ventilation parameters (Table S2). Briefly, kitchens in Michoacán typically incorporate the kitchen and dining room with a mean volume of 41 ± 20 m^3 (n = 627 measurements). In regard to time, women usually start cooking in the early morning. For Mexican customs in rural areas, there are no cooking events (breakfast, lunch, and dinner); instead, there is a period of operation in which the cooks cook foods that include tortillas (tortillas are a garnish of any dish at any time of day), breakfast, and dinner. The mean operating period per day of the stoves is extensive 259 ± 123 min (n = 30 measurements) and similar to that reported by Armendáriz-Arnez et al.[13] When one considers nominal air exchange rate, kitchen designs in rural Michoacán are diverse: without walls, three walls, four walls, brick walls, and wood plank walls with and without gaps, which affects the air exchange between the kitchen and the exterior. Armendáriz-Arnez et al.[13] reported 43% with wooden planks and gaps <1 cm, 33% with gaps <1 cm, and 19% without gaps. Typically, however, in these regions, kitchens have four walls made of wooden planks with gaps of approximately 1 cm,[13,14] a door, and one window. Air exchange rates were estimated after Traynor et al. using CO decay rates in a test kitchen (Figure S2) with similar volume and construction as a typical kitchen (n = 31 measurements).[15] CO decay rates were measured with Q-Trak (Model 7575, TSI

Table 1. Fugitive Emissions from Plancha-Type Stoves in Mexico[a]

		$PM_{2.5}$ emissions rate (mg/min)			CO emissions rate (mg/min)		
parameter	n	chimney	fugitive	fraction of overall	chimney	fugitive	fraction of overall
ONIL	15	52 (32)	2.1 (1.3)	0.05 (0.03)	594 (332)	12 (12)	0.02 (0.02)
Ecostufa	15	75 (52)	3.5 (1.9)	0.06 (0.04)	931 (588)	5 (3)	0.01 (0.01)
Mera-Mera	15	76 (47)	2.4 (1.6)	0.03 (0.02)	1244 (543)	20 (16)	0.01 (0.01)
Patsari	15	50 (21)	3.9 (2.1)	0.07 (0.03)	1645 (965)	11 (11)	0.01 (0.00)
all stoves	60	63 (41)	3.0 (1.8)	0.05 (0.03)	1104 (743)	12 (12)	0.01 (0.01)

[a] Mean (standard deviation).

Table 2. Estimates of 24 h Mean Indoor Concentrations and Percent of Simulations Meeting WHO Air Quality Guidelines and Interim Target 1

	particulate matter $PM_{2.5}$ ($\mu g\ m^{-3}$)				percent meeting annual WHO guideline			carbon monoxide ($mg\ m^{-3}$)					
	mean (SD)	median	10%	90%	interim target-1 ($35\ \mu g\ m^{-3}$)	AQG ($10\ \mu g\ m^{-3}$)	ISO IWA indoor emission $PM_{2.5}$ mg min^{-1}	mean (SD)	median	10%	90%	percent meeting 24 h WHO guideline AQG ($7\ mg\ m^{-3}$)	ISO IWA indoor emission CO g min^{-1}
ONIL	10 (6)	9	5	17	99%	58%	3	0.06 (0.04)	0.05	0.02	0.1	100%	4
Ecostufa	17 (10)	15	9	28	96%	17%	3	0.02 (0.01)	0.02	0.01	0.04	100%	4
Mera-Mera	12 (7)	10	5	20	99%	48%	3	0.10 (0.06)	0.09	0.04	0.16	100%	4
Patsari	19 (11)	17	9	31	94%	13%	3	0.05 (0.03)	0.05	0.02	0.09	100%	4
all plancha stoves	15 (9)	13	7	25	97%	30%	3	0.06 (0.04)	0.05	0.02	0.11	100%	4
LPG	4 (2)	3	2	7	100%	98%	4	0.15 (0.09)	0.14	0.07	0.26	100%	4

Inc., Shoreview, MN) every 2 s, located at a height of 1.5 m in a room with a mixing fan to ensure well mixed concentration.

2.2.1. Impacts of Emissions on Neighborhood Pollution. Smoke temperatures were assumed to be 318 °C based on measured flue gas temperatures at the top of the flue of plancha stoves during performance testing, and exit velocities were 0.5 m/s (Table S2). Other sources of air pollutants can (and often do) increase background ambient concentrations. Similar to the single zone model used to derive emission rates for stoves to meet indoor air quality guidelines and interim targets,[6] background ambient concentrations were not incorporated into the model as the objective was to determine emission rates that would result in an incremental increase in exposures. These concentrations can be readily incorporated on the basis of the local context, but since background ambient concentrations vary widely, the results are of limited application. Wind speeds were based on local wind speeds in the Purepecha region. On the basis of a logarithmic profile, wind speed near the ground would be expected to be lower than wind speed typically measured at a height of 10 m for meteorological data. Low wind speeds are conservative as higher wind speeds would increase particulate dispersion and result in lower estimates of exposure. The criteria for dispersed settlements based on minimum distances between homes were also conservatively estimated to be protective of health by minimizing the dispersion of the plumes by wind and estimating the distance directly downwind based on the center of the plume.

3. RESULTS

3.1. Pollutant Emissions Rate (CO and $PM_{2.5}$).

Table 1 shows fugitive emissions rates of $PM_{2.5}$ and carbon monoxide (CO) from four plancha stove types and the relative fraction of fugitive emissions to the overall emission rate from the stove.

Fugitive $PM_{2.5}$ emissions from the Patsari stove were 1.6 times those from the Mera-Mera, while chimney emissions from the Patsari were ~34% lower. As a result, fugitive emissions from the Patsari are a larger fraction of overall emissions from the stove compared to the stoves with greater chimney emissions. The fractions of fugitive emissions for $PM_{2.5}$ were also substantially higher than those for CO, which may be the result of a greater fraction of $PM_{2.5}$ emissions escaping during lighting or from larger fuel pieces that stick out of the entrance to the combustion chamber.

In controlled testing, the fractions of fugitive emissions from plancha-type stoves were substantially lower than the mean of 25% of the overall emission (standard deviation of 10%; range 1−50) guidance by the World Health Organization (WHO) Indoor Air Quality Guidelines for the fraction of emissions entering the kitchen. The average fugitive emission for the 4 stove types tested was 5 ± 3% for $PM_{2.5}$ emissions and 1 ± 1% for CO emissions. As a result, ISO tier performance should be assessed through direct measurement of fugitive emissions combined with local ventilation parameters for input into the single zone model.

Table 2 and Figure 1 show estimates of the impact of fugitive emissions on indoor air quality using the Monte Carlo single zone model, the percentage meeting WHO air quality guidelines and interim targets, and the ISO IWA 11:2012 indoor emissions tiers of performance. The impact of LPG emissions, assuming all emissions enter the room, have been added for comparison as LPG is often cited as a clean-burning cooking fuel.

The means for each distribution of $PM_{2.5}$ concentrations ranged from 10 to 19 $\mu g/m^3$ depending on the stove; all are below the WHO Interim Target-1 of 35 $\mu g/m$.[3] The means of the CO (24 h) distributions ranged from 0.02 to 0.10 mg/m^3 depending on the stove, which are well below the WHO Air

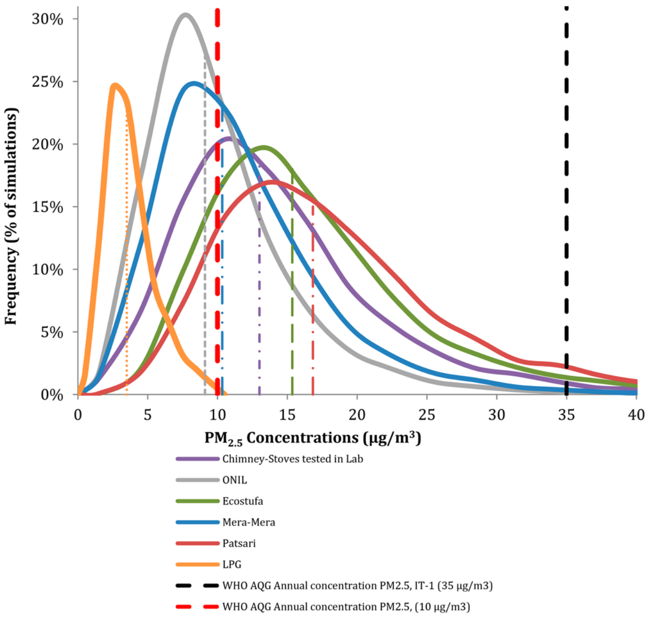


Figure 1. Modeled 24 h mean indoor air concentration distributions of PM$_{2.5}$ from plancha-type stoves and LPG in reference to WHO IAQ guidelines. Vertical bars show geometric means.

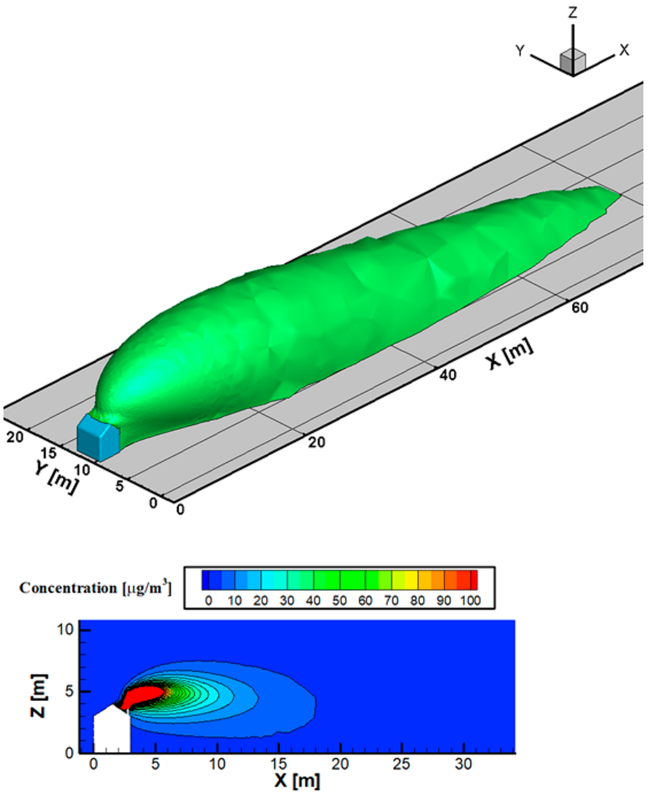


Figure 2. Pollutant plume using iso-surface of concentration (C) of 1 μg/m^3 for emission rate of 40 mg/min and contour of pollutant concentration with distance X and height Z in the center of the plume.

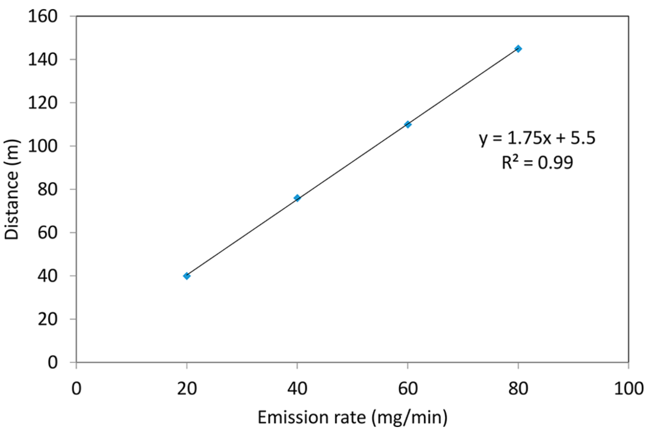


Figure 3. Distance between buildings for PM$_{2.5}$ emission concentration to decrease to 1 μg/m^3 for different chimney emission rates.

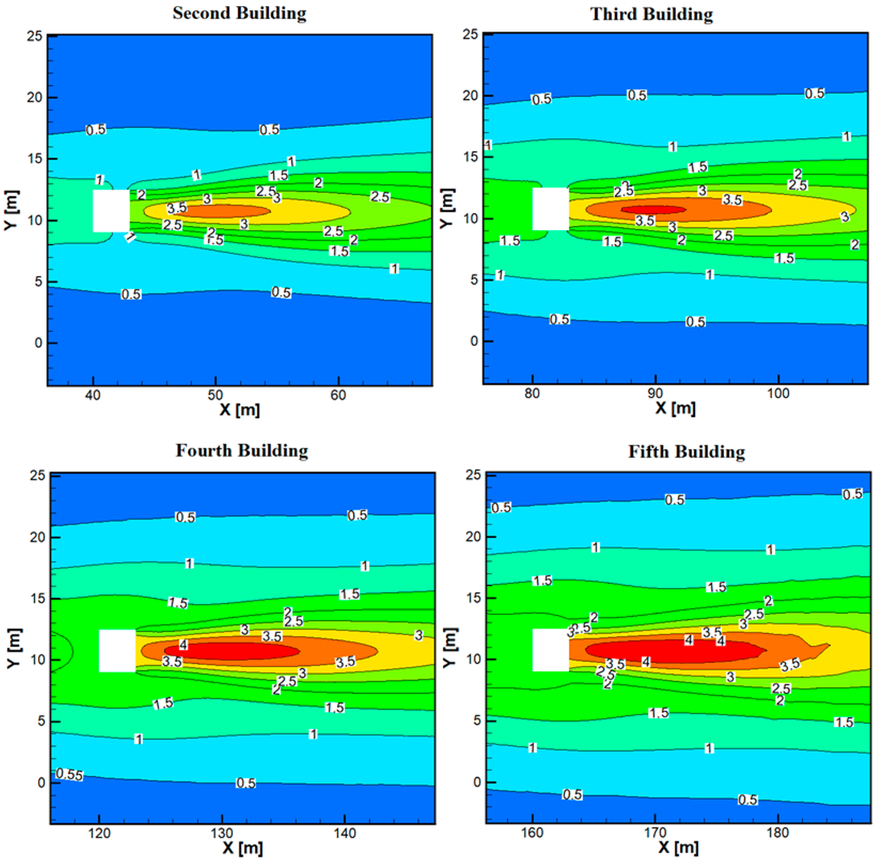
Quality Guideline (AQG) of 7 mg/m^3 recommended by WHO.[16] Fugitive emissions of PM$_{2.5}$ from plancha-type chimney stoves resulted in simulated incremental increases in indoor concentrations of PM$_{2.5}$ that would meet WHO Interim Target 1 for greater than 97% of homes. In addition, for the best performance of these stoves in terms of fugitive emissions, 58% of homes would have an incremental increase in indoor concentrations of PM$_{2.5}$ that was less than the WHO AQG. Overall indoor air concentrations were a factor 2.5−4.7 higher than similar homes simulated with LPG stoves, which is reflected in the percentages of homes meeting the AQG for PM$_{2.5}$. ISO IWA indoor emission tiers for CO were all Tier 4 for plancha-type stoves. Using emissions rates from laboratory tests of LPG reported by Shen et al.[17] and the same single zone model parameters as above, mean indoor PM$_{2.5}$ concentrations were 1.0 ± 0.6 μg/m^3.

In order to estimate the impact of plancha-type stove emissions on surrounding houses downstream, a three-dimensional computational fluid dynamics (CFD) analysis was performed to determine housing densities where plancha-type stoves could be promoted without major neighborhood pollution effects in surrounding houses. Using parameters estimated for the Purepecha region of Mexico on wind speed, housing volume, ground roughness, gas temperature, etc. (Table S2), plume concentrations were estimated for emission rates of 20, 40, 60, and 80 mg/min. Although average values for wind speed were used, plume concentrations will depend on local wind speeds and other meteorological parameters. Figure 2 shows the iso-surface of concentration is equal to 1 μg/m^3 for the emission rate of 40 mg/min and contour of pollutant concentration with distance and height in the center of the plume.

Figure 3 shows the distance between buildings for emission concentration to decrease to 1 μg/m^3 at the breathing height of the individual for different chimney emissions rates. As emissions rates for plancha-type stoves range between 50 and 76 mg/min (Table 1), stoves plumes would decrease to 1 μg/m^3 at an average of approximately 93 m for the Patsari, 96 m for the ONIL, 136 m for the Ecostufa, and 136 m for the Mera-Mera, with an average of 115 m for all chimney stoves.

4. DISCUSSION

4.1. Fugitive Emissions. Chimney and fugitive emissions from four widely disseminated Mexican wood burning plancha-type chimney stoves were measured to allow better estimation of indoor air concentrations and neighborhood air pollution impacts on other village houses downstream and relative health benefits that may accrue from promotion of plancha-type stoves. Measurements show that fugitive emissions from well-functioning chimney stoves are a smaller fraction of total


Second Building

Third Building

Fourth Building

Fifth Building

Figure 4. Contour of pollutant concentration at 1.5 m for 5 homes downwind in the center of the plume with each home emitting at 20 mg/min and a distance of 40 m between homes.

emissions than estimated for the WHO defaults of fraction of emissions entering the kitchen. Plancha-type chimney stoves vent on average 95 ± 3% and 99 ± 1% of total $PM_{2.5}$ and CO emissions out of the kitchen, respectively. Models that link emissions from cookstoves with indoor concentrations of $PM_{2.5}$[18] have been useful in evaluating which stove types would meet WHO air quality guidelines in indoor environments.[6] Using a Monte Carlo single zone model parametrized for local Mexican building ventilation rates, building volume, and cooking time, 24 h IAP concentration levels resulting from these stoves are estimated to be on average 15 ± 9 $\mu g/m^3$ for $PM_{2.5}$ and 0.06 ± 0.04 $\mu g/m^3$ for CO. Modeled concentrations showed good agreement with estimated 24 h mean indoor concentrations from Blanco et al.[19] of 19.9 ± 42.6 $\mu g/m^3$ and 1.6 ± 3.5 mg/m^3 for $PM_{2.5}$ and CO, respectively, based on indoor concentrations during water boiling tests using Patsari and ONIL stoves in a simulated kitchen with dimensions similar to that modeled in the current study. On the basis of these models, plancha stoves meet benchmarks for WHO Air Quality Guidelines (AQG) Interim Target I for $PM_{2.5}$ and the 24 h AQG for CO, with on average 92% of homes meeting the guideline for $PM_{2.5}$. Similarly, all four plancha-type stoves were ISO Tier 4 for indoor emissions of CO and Tier 3 for indoor emissions of $PM_{2.5,}$ respectively.

The Global Alliance for Clean Cookstoves considers stoves that meet ISO IWA Tier 3 for indoor emissions as "clean" for health.[20] Leaving aside issues related to the basis for this classification, modeled indoor air concentrations using the Monte Carlo single zone model based on fugitive emissions measured in the current study implies that the most disseminated Mexican stoves would meet this classification. Thus, these measurements suggest that significant benefits to indoor air quality can result from venting emissions outside the home through a chimney. While it is clear that the best/cleanest options which can feasibly displace traditional stove use should be pursued in different regional contexts, this may include chimney stoves in areas where the use of clean fuels is limited by distribution networks, local infrastructure, fuel pricing, political climate, affordability, and other factors. The benefits of venting outdoors have largely been overlooked by the most recent generations of forced draft stoves. Recent measurements of some of these stoves however have shown that exposure reductions have failed to materialize in uncontrolled field trials.[21,22] When used in indoor kitchens, ventilation of these stoves with flues or chimneys, however, likely would have achieved substantial exposure reductions provided that traditional stoves were not used alongside stoves with chimneys. Clearly, there are a range of other barriers and complications in installing chimneys; however, the benefits may merit the extra effort, and many stoves globally incorporate chimneys including heating stoves in China[21,23] and Mongolia,[24] among others, and plancha-type stoves across Central America. When used outdoors, emission rates can be substantially higher and still maintain exposure contributions below WHO air quality guidelines.[25]

4.2. Contribution to Neighborhood Emissions.

Although indoor fugitive emissions from Mexican plancha-type stoves meet GACC criteria for being "clean" in indoor kitchens, there are clearly scenarios where promotion of typical plancha-type stoves would not be advisable due to the density of surrounding homes and the neighborhood pollution impacts of the emissions vented through the chimney (although more advanced plancha-type stoves with cleaner combustion or alternative fuels may resolve some of these concerns). Indoor pollutant concentrations in a kitchen with a plancha stove are a function of fugitive emissions from the stove, reinfiltration of emissions from the chimney of the same stove back into the home, and infiltration of ambient pollutants from other external sources and upstream village stoves. Aside from important considerations related to user preferences, adoption, use intensity, and purchasing power, from a health perspective, determination of whether plancha stoves should be promoted in an area depends on the density of homes that contribute to downwind neighborhood pollution levels and relative costs and accessibility of cleaner fuels.

Determination of whether the indoor air concentrations are lower than WHO AQG and Interim Targets depends on the ambient concentrations upwind, which are a function of the density of homes in the area where dissemination of plancha-type stoves are being considered. To provide a benchmark for criteria for where dissemination of stoves could be considered, three-dimensional computational fluid dynamics (CFD) analysis was used to estimate the distance required between homes for chimney emissions outdoors to drop to 1 $\mu g/m^3$ between homes. As a first step, these criteria can be useful in spatial analyses to evaluate potential areas where installation of plancha-type stoves could be promoted where the emissions do not substantially increase neighborhood pollution levels, an approach similar to that used for estimating impacts of outdoor cooking on neighboring houses.[25] Consequently, a mechanistic model was used to evaluate plausible contributions to the neighborhood pollution impacts from houses with similar emissions spaced equally downwind in the center of the plume and resultant health implications. Figure 4 shows plume concentrations at the breathing height of an individual (1.5 m) for 5 houses in the downwind direction with each home emitting at 20 mg/min and a distance of 40 m between homes such that the emissions from the first house reach 1 $\mu g/m^3$ at the second home.

Figure 4 demonstrates the increase in neighborhood pollution as we move downwind, as a result of pollutant emissions from houses upwind, which is countered by plume dispersal. Since the distance between homes is linearly proportional to the emissions rate, for the Patsari stove, Figure 5 shows the incremental increase in concentration in neighborhood pollution for homes spaced 100 m apart such that emissions from the first house reach 1 $\mu g/m^3$ at the second home. The figure demonstrates that neighborhood pollution impacts reach 4 $\mu g/m^3$ by 8 km or 80 homes downstream under this scenario. When added as background concentrations to the Monte Carlo single zone model simulation, plancha-type stoves would still meet WHO IT1 of 35 $\mu g/m^3$.

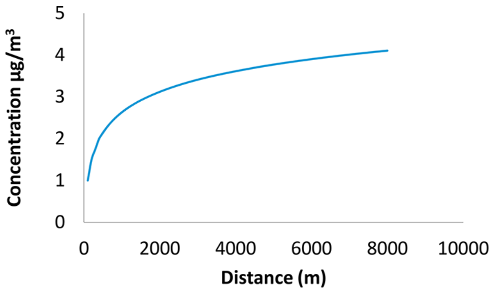


Figure 5. Increase in concentration at each successive building with distance for homes with Patsari stoves spaced 100 m apart.

5. LIMITATIONS

Use of Monte Carlo simulations and three-dimensional computational fluid dynamics (CFD) analysis clearly represents an idealized set of assumptions and scenarios that are not intended to represent actual communities, rather they are intended to facilitate the establishment of benchmarks that can be further evaluated and tested with field measurements. In particular, simulated indoor air concentrations are sensitive to assumptions on kitchen ventilation (airflow and mixing volume). Although ventilation rates were measured in a kitchen with similar construction, dimensions, and door/window openings as the average kitchen in these regions of Michoacán, in practice, kitchens vary considerably particularly where self-built structures are not standardized. These simulations do not capture the range of variability in kitchen design or the actual indoor air concentrations in individual kitchens; rather, they are intended to give an idea of indoor air concentrations in a typical kitchen for the region. Similarly, there are many differences in kitchen construction and design in different climatic conditions in Mexico and other regions of the world, which would impact kitchen ventilation and indoor air concentrations and, thus, the number of simulations and homes meeting guidelines. For example, Park and Lee report lower average air exchange rates of 12.2 air changes per hour (ACH) in 18 homes based on CO decay for a single event of 7 min or longer. Actual air exchange rates were likely higher however as they assumed zero background CO concentration, well mixed air, and no CO source strength during the decay although the source was not removed from the room.[26] CO emissions can be very significant in the smoldering phase of the fire, and emissions are typically quite stratified and not well mixed in village kitchens. Smith et al. estimated that air exchanges greater than 35 ACH would be required for their modeled concentration to agree with measured concentrations in Indian village homes.[27] Bhangar reported mean air exchange rates of 15.8 ± 4.04 ACH for 10 homes with mud walls using traditional stoves in Kaldari, India.[28] Cowlin measured 6 kitchens in San Lorenzo Guatemala and reported air exchange rates of 15.8 ± 5 ACH for closed kitchens, 18.3 ± 7.8 ACH for partially closed, and 31.4 ± 18.8 ACH for open homes.[29] In addition, they showed that height of measurement significantly impacts air exchange estimates in open homes when a mixing fan is not present with lower-height measurements producing lower air exchange estimates.[29] In the current study, the mean ventilation rates were substantially higher than many of those reported in the literature but similar to Cowlin estimates for open homes at higher measurement heights. A mixing fan was present in the current study which may account for the higher estimates, and kitchen construction in this region is typically in a separate room from the main house with large eave spaces and ∼1 cm gaps between wall planks. In addition, simulated indoor concentrations agree well with measured concentrations in homes.[19] To evaluate the impact of air exchange rates, therefore, and to illustrate how these stoves might perform in other environments, Figure 6 shows the percent of simulations meeting WHO guidelines under different air exchange profiles with other parameters kept as above. With air exchange rates above 40 ACH, there is not a large

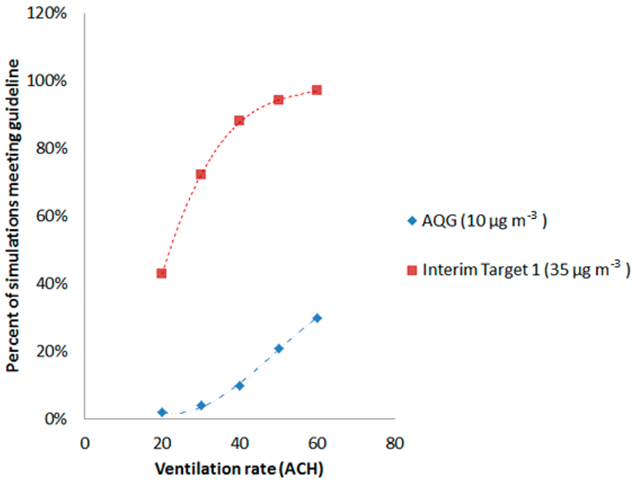


Figure 6. Percent of simulations meeting WHO guidelines under different air exchange profiles.

difference in the number of simulations meeting Interim Target 1 but a significantly greater fraction meeting the air quality guideline. Conversely, the fraction meeting Interim Target 1 decreases rapidly below 30 ACH. Where direct measurements of fugitive emissions are not possible, these results give a baseline for the estimated fraction of simulations meeting the guidelines when combined with local data on kitchen ventilation.

Modeling homes spaced equally apart directly downwind and emitting all at the same time represents an idealized conservative scenario to be more protective of health. While the modeled indoor air concentrations based on the Monte Carlo single zone model agree well with controlled measurements, they differ substantially from actual communities due to the upwind contributions of a variety of sources including homes and small scale industries, variable wind speed in actual communities, temporal (daily and seasonal) differences in emissions, behavior, meteorological parameters, etc. The impact of upwind sources on the effective indoor air reductions seen from plancha-type stove dissemination in communities has been demonstrated by Armendáriz-Arnez et al.[13] While the neighborhood pollution impacts are modeled from stove emissions, the contributions of ambient background emissions from further upstream are not included, as they are spatially and temporally variable in different countries around the world and limit application of these analyses. Background ambient concentrations can be added for different regions, however, to make these analyses more relevant to the local context.

Stacking of cooking stoves (the practice of using more than one stove) has been widely reported in Mexico and other places where households do not transition fully to cleaner burning cookstoves but retain the traditional stove, often outdoors for some cooking tasks.[30] The current analyses do not include stacking in homes as the purpose was to evaluate the potential benefits of plancha-type stoves and to determine spatial criteria where these stoves could be promoted. Similar to LPG, where stacking occurs and the traditional fire is used indoors for some tasks, air quality guidelines may not be met. However, in this region, use of the traditional fire in combination with the plancha-type stove tends to be in outdoor environments for heating water.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b01704.

> Emissions hood configuration; test kitchen; Monte Carlo and CFD model parametrizations; locally measured housing characteristics and ventilation parameters; CFD methodology validation (PDF)

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Notes

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